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Intelligent Control of Rehabilitation Robot: Auto Tuning PIDController withInterval Type 2 Fuzzy for DC Servomotor

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Abstract

DC servomotors have been in use extensively for many applications vary from industrial to robotics to consumers. DC servomotors provide error feedback signal to its PID controller to minimize the error. However, its conventional PID controller still causes several problems such as poor accuracy in non-linear systems and poor response when there is frequent disturbance. In this research, atuning method for PID controller, i.e., Interval Type-2 Fuzzy Logic for DC servomotor is proposed. The paper proposes error and error derivative are of type 2 fuzzy inputs to the rules and output is the corrective signal to supplement PID output. Detailed methodology and work results show that both type-1 and type-2 fuzzy logic tuning offers better response than conventional PID controller and Interval Type-2 Fuzzy Logic handles uncertainties better than Type-1. This could be used as intelligent control in Rehabilitation Robots. In addition, it also provides promising potentials in robotics and medical applications that require high precision and quick response such as medical diaphragm pump, infusion pump, pharmaceutical dispenser, minimally invasive surgery, etc.

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1. Introduction

Servomotors are used for precise positioning and speed control to provide feedback signal for closed loop control scheme to improve control performance [1]. DC servomotors have been widely in use for decades in various applications such as robotics, automatic steering, radar tracking, computer disk drives, and industrial manufacturing robots etc. The most basic and prevailing continuous feedback controller is PID controller. PID controller regulates the corrective signal based on the error between output feedback signal and expected output signal. There are still several problems with PID control such as: low efficiency in non-linear system, degraded performance with disturbance, and requirement of manual tuning. Many researchers have attempted to mitigate these defects utilizing genetic algorithm, neural network, sliding-mode control, and fuzzy logic.

Fuzzy logic concept was introduced by professor Zadeh [2] in 1965 to deal with uncertainties. The main objective of fuzzy logic is to provide electronic devices the ability of dealing with variables which have no strict boundaries of variation. Basically, fuzzy logic governs the control system output with IF – THEN rules, which is close to human reasoning,

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e.g., if food is delicious and service is good then tip is high. This can be applied for tuning DC servomotor PID controller with rule inputs as error and the derivative of error and rule output is the corrective signal magnitude.

There have been several works [1, 3, 4, 5, 6, 7, 8] that tried to better the PID controller performance specifically for DC servomotor. In these works, Genetic Algorithm [1], Type-1 Fuzzy PD Controller [3], Type-1 Fuzzy Self Tuning [4], Neural Networks with Single Neuron [5], First-order Sliding Mode Control [6], Adaptive Control Scheme [7] and Intelligent Neural Network [8] were employed where it was found there are limitations in terms of slow settling time, high overshoot during load change, significant chattering, excite high-frequency unmodeled dynamics, and slow and noisy step response amongst others.

Recently in intelligent control, DC servomotor control using type 1 fuzzy logic (T1FL) is quite popular with many researches like [9], [10], [11], and [12]. However, the initial fuzzy logic concept did not completely solve imprecise problems since there are still uncertainties within itself [13]. These remaining uncertainties may come from the fuzzy sets that were defined arbitrarily (no guaranty of precise range) or from the noisy numerical data, inaccurate measurement, or disturbance [14]. For improvement of original fuzzy logic (type 1 fuzzy logic), in 1975, professor Zadeh introduced type 2 fuzzy logic (T2FL) that increases 1 more degree of freedom to handle uncertainties [15]. DC motor control using Fuzzy Type 2 has been given in [16 and 17].

This paper discusses the findings of the use of auto tuning PIDcontroller with Interval Type 2 Fuzzy Logic for DC servomotor. The paper is arranged in three sections as follows. The concept of fuzzy logic tuning for PID controller is presented in section 2. It comprises of the Dc motor model, fuzzy inference system concept, type 1 fuzzy logicPID tuning, type 2 fuzzy logic concept and PIDtuning. Section 3 shows the results and explorative analysis to validate the proposed tuning method, and finally section 4 concludes the paper.

2. Proposed Work

2.1. DC servomotor modeling

The DC Servomotor model is based on assumption given in [1] with the following parameters:

V_a	input voltage, V
θ	output angular position, rad
ω	output angular velocity, rad/s
V_{emf}	back emf voltage, V
J	moment of inertia of the rotor, kg.m ²
K_f	motor viscous friction constant, N.m.s
K_b	electromotive force constant, V/rad/s
K_m	motor torque constant, N.m/A
R	electric resistance, Ω
L	electric inductance, H
T_d	torque load disturbance, N.m

The block diagram for a DC servomotor is given in Figure 1.

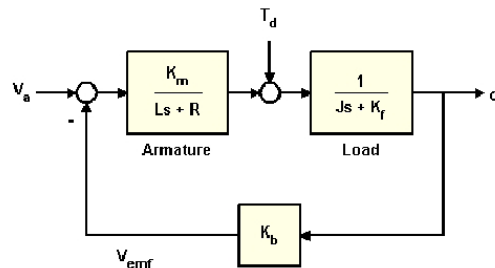


Fig.1. DC servomotor modeling block diagram

Open-loop transfer function if the rotational angular velocity $\omega(s)$ is considered the output and the armature voltage $V_a(s)$ is considered the input as given below in Equation (1):

$$G(s) = \frac{\omega(s)}{V_a(s)} = \frac{K_m}{(Js + K_f)(Ls + R) + K_b^2} \quad (1)$$

2.2. Fuzzy inference system

Figure 2 gives outline for tasks that an inference system performs, including:

- Fuzzification: transform crisp input(s) into fuzzy sets with membership functions.
- Combination: combine input(s) with corresponding operators AND, OR and NOT.
- Rules processing: produce desired consequence(s) from combined input(s) based on rules that were defined in rule base.
- Consequence(s) aggregation: combine consequence(s) to get a united output.
- Defuzzification: transform the single output fuzzy set back crisp value.

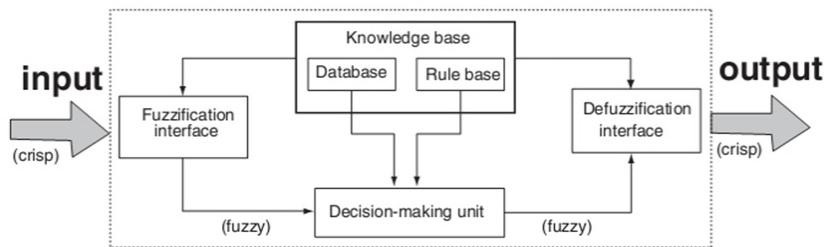


Fig.2. Inference System Outline

2.3. Type 1 Fuzzy Logic Tuning for PID Controller

The application of type-1 fuzzy logic into tuning PID controller is implemented based on the idea that error and rate of error change are 2 fuzzy set inputs for fuzzy inference system to produce output as corrective signal. This corrective signal would supplement the PID output signal to control the DC servomotor system. Figure 3 shows the Simulink block diagram of type-1 fuzzy logic tuned PID controller with the DC servomotor model as the subsystem block.

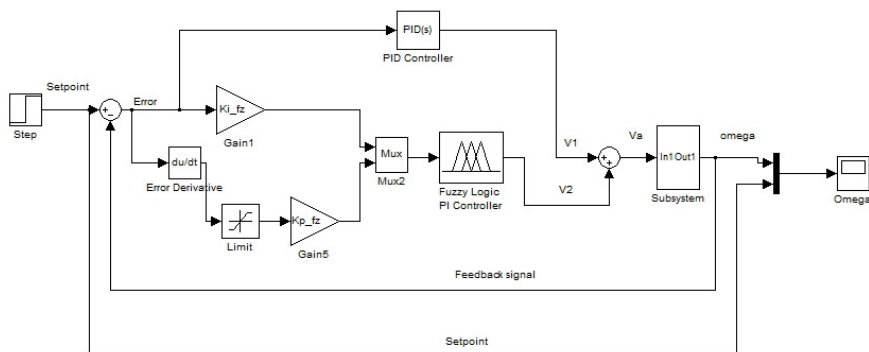


Fig.3. Type 1 fuzzy logic tuned PID controller

Each input (Error and Error Derivative) to the fuzzy logic block comprises of 3 membership functions, namely *thenegative*, *zero* and *positive*. The rules of fuzzy logic inference system to determine supplementing corrective signal are given in Table 1.

Table 1. Rules Table

DE \ E	n	o	p
n	n	n	o

o	n	o	p
p	o	p	p

where:

E is the error, DE is the change rate of error (derivative of error), n is negative, o is zero and p is positive.

The rules can be interpreted as:

- R1: IF E is n (negative) and DE is n (negative) THEN output is n (negative)
- R2: IF E is n (negative) and DE is o (zero) THEN output is n (negative); and so on.

2.4. Type 2 Fuzzy Logic Tuning for PID Controller

2.4.1 Type 2 Fuzzy Logic Concepts

Type 2 fuzzy sets are the extended version of original (type 1) fuzzy set. In type 2 fuzzy sets, the membership function itself is a fuzzy concept. Interval type 2 fuzzy sets prevail compared to type 1 due to its simplicity and the incapability of proving any better candidate [13]. Due to the complicated nature of type 2 fuzzy sets, the work flow for type 2 fuzzy inference system is upgraded. The corresponding inference system for type 2 fuzzy logic is as given in Figure 4.

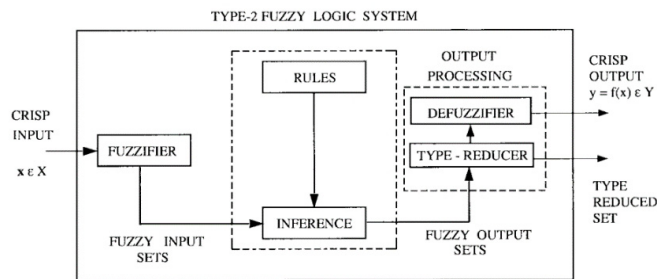


Fig. 4. Type 2 fuzzy logic inference system

Compared to type 1 inference system, type 2 has 1 more block that is “type reducer”. The role of this block is to convert a type 2 fuzzy set to a simple type 1 set so that defuzzifier can transform it to a crisp output for further application.

2.4.2 Type 2 fuzzy logic tuning for PID controller

Figure 5 shows the Simulink block diagram of type 2 fuzzy tuned PID controller. The Interpreted Matlab Function block represents Matlab code of type 2 fuzzy inference system.

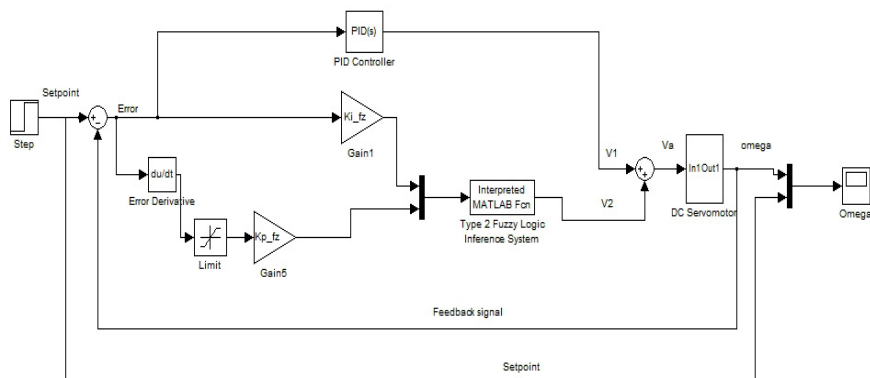


Fig. 5. Type 2 fuzzy logic tuned PID controller

The Error and Error Derivative interval type 2 fuzzy sets are presented in Figure 6.

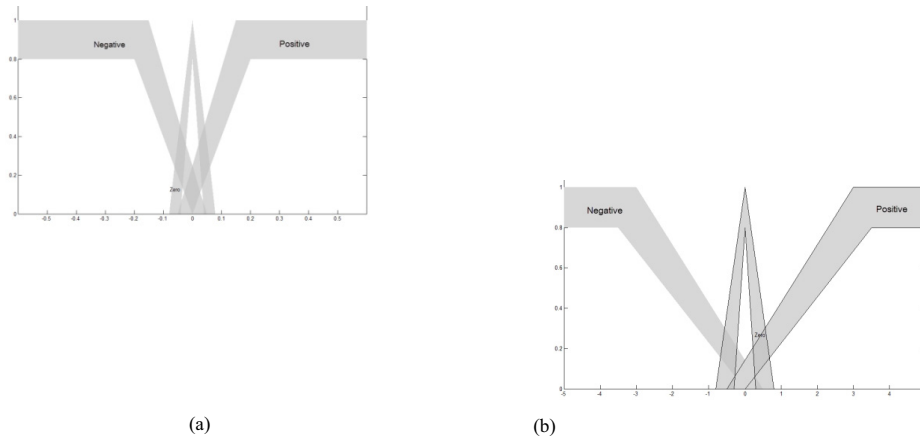


Fig. 6. Type 2 fuzzy sets (a) Error (b) Error Derivative

This research utilizes center-of-set type reduction for type 2 fuzzy reference system. This method replaces rule consequent type 2 fuzzy set by a singleton at its centroid and then find the centroid of the type 1 fuzzy set comprised of these singletons [18]. The algorithm to be implemented is enhanced iterative algorithm with stop condition (EIASC)[19]. The rules for interval type 2 fuzzy inference system are given in Table 2.

Table 2. Rules table for interval type 2 fuzzy system

DE \ E	n	o	p
n	$Y^1 = [-300, -200]$	$Y^2 = [-100, 0]$	$Y^3 = [-100, 100]$
o	$Y^4 = [-100, 0]$	$Y^5 = [-50, 50]$	$Y^6 = [0, 100]$
p	$Y^7 = [-100, 100]$	$Y^8 = [0, 100]$	$Y^9 = [200, 300]$

3. Result and Discussion

The simulation is conducted to test for unit step responses of conventional PID controller, type 1 fuzzy tuned and interval type 2 fuzzy tuned. The error signal for 3 systems is added with the same uniform distributed noise at different magnitude limit. Beside the noise in error, test is expanded further with DC servomotor varying loads at certain moments. Main criteria to assess performance are Integral Absolute Error (IAE) and Integral Time Absolute Error (ITAE).

3.1. Test under no varying load

Without any change in motor load, the noise absolute magnitude to be added in error signal is consequently 0.1; 0.15 and 0.2. That means the maximum error noise is 20% of step change. Under 0.1 noise magnitude, the responses are given in Table 3 and shown in Figure 7. Under 0.15 noise magnitude, the responses are given in Table 4 and shown in Figure 8.

Table 3. Result with no varying load, noise is 0.1

	PID	Type 1 fuzzy tuned PID	Interval type 2 fuzzy tuned PID
IAE	0.1277	0.1414	0.107
ITAE	0.0006467	0.000715	0.0005432
Overshoot	11%	4%	2.5%
Rise time	0.109	0.105	0.103

Table 4. Result with no varying load, noise is 0.15

	PID	Type 1 fuzzy tuned PID	Interval type 2 fuzzy tuned PID
IAE	0.1601	0.1794	0.1298
ITAE	0.0008084	0.000905	0.0006572
Overshoot	12%	5.7%	3.7%
Rise time	0.109	0.101	0.102

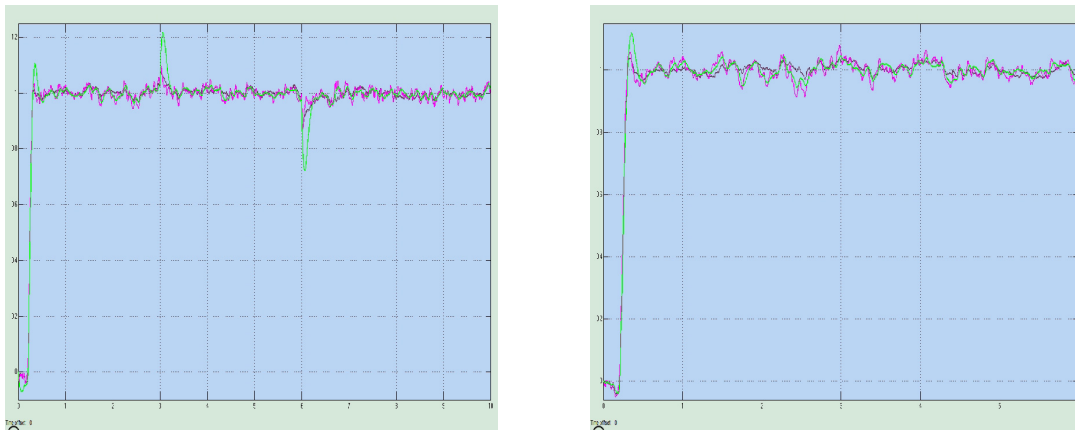


Fig. 7. Step responses with varying load, noise = 0.1 Fig. 8. Step responses with varying load, noise = 0.15

— PID controller
 — Type 1 fuzzy tuned PID
 — Interval type 2 fuzzy tuned PID

The conclusion can be drawn from tests with different noise absolute magnitudes and no varying change is that interval type 2 fuzzy tuned PID offers the smallest IAE and IATE, smallest overshoot and also smallest rising time. Type 2 fuzzy tuned PID produces the best results.

3.2. Test with varying load

The simulation is carried out for 10 seconds with DC servomotor initial load is different than zero and load changes at $t_1=3s$ and $t_2=6s$. The noise to error signal is the same with previous test as consequent magnitudes are 0.1; 0.15 and 0.2. The results are tabulated respectively in Tables 5 and 6, and shown in Figures 9 and 10 respectively. It is observed in Figure 10 that at $t_1=3s$ and $t_2=6s$, when the load changes, there are overshoots that is significant and this can be used as an additional factor to assess performance of controllers.

Table 5. Result with varying load, noise is 0.1

	PID	Type 1 fuzzy tuned PID	Interval type 2 fuzzy tuned PID
IAE	0.2437	0.2172	0.1806
ITAE	0.001226	0.001094	0.0009109
Overshoot 1	10.7%	3.6%	1.3%
Overshoot2	22%	10.2%	7.5%
Overshoot3	28%	12.9%	12.2%
1 st Rising time (s)	0.101	0.1073	0.1085

Table 6. Result with varying load, noise is 0.15

	PID	Type 1 fuzzy tuned PID	Interval type 2 fuzzy tuned PID
IAE	0.297	0.2785	0.2137
ITAE	0.001493	0.0014	0.001076
Overshoot 1	11.7%	5%	1.8%
Overshoot 2	22.8%	9.25%	8.35%
Overshoot 3	28.6%	16%	13.2%
1 st Rising time (s)	0.109	0.103	0.106

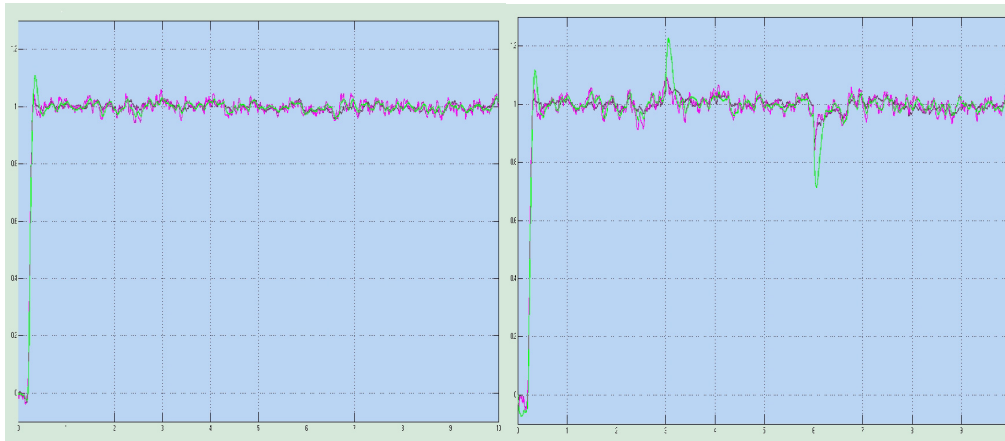


Fig.9. Step responses with varying load, noise = 0.1 Fig. 10. Step responses with varying load, noise = 0.15

Again, when testing with new condition of changing load, interval type 2 fuzzy tuned PID continues to prevail over conventional PID and type 1 fuzzy tuned PID. Although sometimes rising time of interval type 2 is bigger than the others, its smaller IAE and ITAE have justified its position as the best controller.

4. Conclusion

This paper has discussed the auto tuning PID Controller with Interval Type 2 Fuzzy Logic for DC servomotor where it was found that Interval Type 2 Fuzzy Logic controller is proven to be more efficient than conventional PID controller and type 1 Fuzzy Logic controllers in both varying no load and varying load conditions in terms of system performance parameters such as IAE, ITAE, overshoot and rising time. This is a strong foundation for the continuity of work in Interval Type 2 Fuzzy Logic application to tune conventional PID controller more efficiently. This also provides promising potentials in robotics and medical applications that require high precision and quick response such as medical diaphragm pump, infusion pump, pharmaceutical dispenser, minimally invasive surgery.

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